Improvement of Human Safety in Fault-Tolerant Human and Robot Collaboration Using Convex Optimization and Receding Horizon Control

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Robotics in industries: 2016

- 34,606 robots ($1.9 billion) were ordered in North America: growth of 10%
  - The automotive industry: 25% growth
  - Assembly applications: 61% growth
  - Spot welding: 24% growth
  - The food and consumer goods industry: 32% growth

- Robotic Industries Association
Robotics in industries: 2025

- Replacing 16% of jobs in US
- Creating nearly 9,000,000 (9%) new jobs in new fields like robot monitoring, data science and content curation
- Net value: Impacting 7% of jobs

- Forrester Research
Robotics in industries

What if a task needs the intelligence and flexibility of human and accuracy and repeatability of a robot?

Collaborative Robots
Collaborative Robots

- Designed to be safe around people
- Easy to program, even via a smartphone or tablet
- Easy to be moved from task to task as needed
- Intended to assist, not replace human workers
- Lightweight
- Simpler than more traditional robots
- Cheaper to buy, operate and maintain
Safety

• Accidents happen when the human worker is inside the work cell
  o Human interferes with robot normal motion
  o A failure in robot causes sudden and harmful motion

*The Telegraph*, July 2015:
A robot has killed a contractor at one of Volkswagen's production plants in Germany where a 22-year-old man was setting up the stationary robot.

*The Times of India*, August 2015:
Sharp welding sticks jutting out of the robotic arm of a machine pierced a worker killing him at a factory. The worker had moved too close to the robot while adjusting a metal sheet that had come unstuck.
Safety

• Robophobia: An anxiety disorder in which sufferers have an “irrational fear of robots, drones, robot-like mechanics, or artificial intelligence.”

  Psychologist Dr. Graham Davey, 1997

• Symptoms: panic attacks, sweating, anxiousness, discomfort, kicked off by either the sight of a robot, being near a robot, or even just talking about robots.

In 1997, 20% of the world’s population were suffering from robophobia.
Safety

• Solutions:
  o Physical safety barriers
  o Limits on robot motion
  o Limits on robot forces
  o Proper installation of robot
  o Use force/torque controls

Productivity?
Safety vs Productivity

Safety first, but also be more productive

Collision-free motion planning algorithm

Recovery from failure
Problem & Solution

- Optimal path planning for end-effector and collision avoidance
Problem & Solution

- Optimal path planning for end-effector and collision avoidance

Problem & Solution

- Optimal fault-tolerant trajectory planning for joints and collision avoidance
Problem & Solution

Develop new algorithm that:
- Optimally plans motion of robot
- Avoids collision with human
- Completes the task safely after failure
- Minimizes velocity jumps after a failure in actuators

Motion capture system

Part to be assembled

Operator's hand tracked by the system

Robot's end-effector follows the operator's hand

Monitored distance

Following

Parts of the scene considered as background

Operator

NIOSH Expanding Research Partnerships: State Of The Science Conference, June 2017, Aurora, CO
Methods And Approaches

- Receding Horizon Control
  - Predicts and plans for next $K$ steps in each iteration
  - Executes only the first step in each iteration
  - Re-plans after each step

✓ Make a smooth trajectory
✓ Decrease computational time

Changbin Hu 2015
Methods And Approaches

- Convex Optimization

\[ \begin{align*}
\min & \quad f_0(x) \\
\text{s.t.} & \quad f_i(x) < 0 \\
& \quad h_j(x) = 0
\end{align*} \]

- It is convex when:
  - The objective function is convex
  - The inequality constraint functions are convex
  - The equality constraint functions are affine

- Guarantees global optimality

- Used GUROBI optimization package (fastest solver available now)
Methods And Approaches

- Objective function:
  - Minimum path
    \[
    \min \sum_{i=1}^{h} \sum_{j=1}^{p} \left\| z_j(i + 1) - z_j(i) \right\|_2^2
    \]
  - Minimum joints velocity jumps
    \[
    \min \sum_{i=1}^{h} \left\| \dot{q}_j \right\|_2^2
    \]
  - Minimum end-effector tracking error
    \[
    \min \sum_{i=1}^{h} \left\| z_r(i) - z_{nl,m}(i) \right\|_2^2
    \]

\[
\min w_1 \sum_{i=1}^{h} \sum_{j=1}^{p} \left\| z_j(i + 1) - z_j(i) \right\|_2^2 + w_2 \sum_{i=1}^{h} \left\| z_r(i) - z_{nl,m}(i) \right\|_2^2 + w_3 \sum_{i=1}^{h} \left\| \dot{q}_j \right\|_2^2
\]
Methods And Approaches

- Constraints
  - Robot kinematics
    \[
    A_{cs,j}(i)(z_{j,m}(i) - z_{j-1,m}(i)) \leq b_{cs,j}(i)
    \]
    \[
    A_{is,j}(i)\left(z_{j,m}(i) - z_{j-1,m}(i)\right) \geq b_{is,j}(i) + (u_j(i) - 1)M
    \]
    \[
    \sum_{s=1}^{n_{is}} u_{j,s}(i) \geq 1
    \]
  - Obstacle avoidance
    \[
    A_{o}(i)z_{j,k}(i) \geq b_{o}(i) + (v(i) - 1)M
    \]
    \[
    \sum_{s=1}^{n_{is}} v_s(i) \geq 1
    \]
Methods And Approaches

- Constraints
  - Actuator failure modeling
    \[ A_{cs,F}(i)(z_{j,m}(i) - z_{F-2,m}(i)) \leq b_{cs,F}(i) \]
    \[ A_{is,F}(i)\left(z_{F,m}(i) - z_{F-2,m}(i)\right) \geq b_{is,F}(i) + (u_F(i) - 1)M \]
    \[ \sum_{s=1}^{n_{is}} u_{F,s}(i) \geq 1 \]
  - Velocity bounds
    \[ \left| \frac{z_{j,m}(i + 1) - z_{j,m}(i)}{\Delta t} \right| \leq v_{j,max} \]
Simulation and results

- Planar 4-DOF robot
- End-effector trajectory: U-shaped
- 3rd joint fails (locks) at $t=14$ sec
- Human as obstacle
Simulation and results

- Task completion and obstacle avoidance
  - 3rd joint locks at t=14 sec
Simulation and results

- Minimize velocity jumps

![Diagram showing simulation results with curves for different manipulator states and a failure point at 1st joint.](image-url)
Simulation and results

- Minimize velocity jumps
Simulation and results

- Minimize velocity jumps

![Graph showing angular velocity over time for different cases with 3rd joint highlighted]
Simulation and results

• Minimize velocity jumps

![Graph showing simulation results with arrows indicating failure and locked actuator](image-url)
Discussion

- Complete the task safely
- Optimize the joint trajectory
- Avoid having collision with human
- Minimize joints velocity jumps

Improve productivity
Avoid injuries
Improve safety
Conclusion and future work

- Developed an algorithm for improve safety in HRC in advanced manufacturing
- Using motion analysis and machine learning for human motion and intent prediction and perception
- Adding biomechanical constraints, human factors and safety parameters into optimization problem
- Design optimized task assignment between human and robot to improve safety and productivity
Thanks

Questions?